FACT – the First Cherenkov Telescope using a G-APD Camera for TeV Gamma-ray Astronomy

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Abstract

Geiger-mode Avalanche Photodiodes (G-APD) bear the potential to significantly improve the sensitivity of Imaging Air Cherenkov Telescopes (IACT). We are currently building the First G-APD Cherenkov Telescope (FACT) by refurbishing an old IACT with a mirror area of 9.5 square meters and are constructing a new, fine-pixelized camera using novel G-APDs. The main goal is to evaluate the performance of a complete system by observing very high energy gamma-rays from the Crab Nebula. This is an important field test to check the feasibility of G-APD-based cameras to replace at some time the PMT-based cameras of planned future IACTs like AGIS and CTA. In this article, we present the basic design of such a camera as well as some important details.

Keywords: Cherenkov telescope, ground-based gamma-ray astronomy, instrumentation, Geiger-mode Avalanche Photodiode (G-APD)

1. Introduction

Since the first ground-based detection of very high energy (VHE) gamma-rays from outer space in 1989 [1], the field of gamma-ray astronomy with Imaging Air Cherenkov Telescopes (IACT) has made a significant progress, resulting in the detection of more than a hundred known gamma-ray sources of both galactic and extragalactic origin. This achievement was mainly driven by technological developments enabling a giant leap in sensitivity as achieved by the most recent instruments, the CANGAROO-III, H.E.S.S., MAGIC, and VERITAS telescopes. Now the field is standing at the crossroads, seeking another significant increase in sensitivity compared to the currently best instruments for the next generation instrumentation, CTA [2].

As the sensitivity of IACTs depends on the overall photon detection efficiency, i.e., on the conversion of Cherenkov photons reflecting from the primary mirror into measurable photoelectrons, it is only natural to seek for better devices for photon detection. For all IACTs built up to now, Photomultiplier tubes (PMT) have been the first choice. Recently, a new semiconductor device with excellent single photon response became available: the so-called Geiger-mode Avalanche Photodiode (G-APD).

2. Geiger-mode Avalanche Photodiodes

PMTs have been the workhorse in detecting single or few photons ever since their invention. This is mainly due to a photon detection efficiency (PDE) of 20-30% around 300-450 nm wavelength and their high intrinsic amplification ($\mathcal{O}(10^5 - 10^7)$). But due to their

- limited possibilities to further increase their quantum efficiency (QE),

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- sensitivity to even weak magnetic fields,
- needs of stabilized HV power supplies,
- easy damage by high light levels,
- expensive production techniques

one would like to replace them by more advanced devices. With the invention of GAPDs, many of these drawbacks could be overcome by robust semiconductor devices, keeping the high intrinsic amplification and promising even higher PDEs than that of PMTs (for an overview, see [3]): G-APDs are operated at voltages around 70 V, much lower than for PMTs, and they are neither damaged by bright illumination during operation nor sensitive to magnetic fields. Altogether, this makes them promising candidates for replacing PMTs in the next generation of Astroparticle Physics instrumentations, and especially in IACTs [4, 5]. For this purpose, several intrinsic properties of a given G-APD type, including the afterpulse behavior [6], the angular acceptance and the dependence of the charge output on the illumination [7] have been studied especially focusing on their possible application in IACTs. In addition, the first Cherenkov light from air-showers has been detected with an installation of an array of four G-APDs on the MAGIC telescope [8]. In this way, the idea of a two-step test for this new technology to be operated under Cherenkov telescope conditions was developed [9], with the first step evaluating a small test camera consisting of 144 G-APDs (Section 3) and the second step to build a full-size camera operated on an existing Cherenkov telescope (Section 4).

3. The 36-Pixel Test Camera M0

In the first step of the test to study G-APDs as possible replacements in IACTs, a small test camera was built [10]. This camera was made up of 144 G-APDs of the type Hamamatsu MPPC S10362-33-50-C [11]. The signals of groups of four G-APDs were combined in an analog sum to make one pixel. Thus, the camera consisted of 36 pixels being arranged in a 6x6 lattice. The trigger decision was derived from a majority coincidence from the innermost 16 pixels. Upon a trigger, all signals from the 36 pixels were digitized using the Domino Ring Sampling chip DRS2 [12], which is based on a capacitor array, allowing for a high sampling rate of 2 GSamples/s and being read out after a trigger by a fairly slow (40 MHz) ADC system. A similar digitization system, also based on the DRS2, is currently being used by the second MAGIC telescope [13]. This test setup, combined with an 80 cm diameter focusing mirror, served to observe Cherenkov light from VHE air-showers in the presence of the rather bright night-sky background of Zurich. This test proved that it was possible to observe air-showers by a self-triggered camera built entirely of G-APDs [14, 15]. This, and similarly auspicious findings of another group [16] convinced us to design the first real-size Cherenkov telescope equipped with a G-APD camera, FACT.

4. FACT

The First G-APD Cherenkov Telescope (FACT) will be based on a former HEGRA telescope, still situated at the Roque de los Muchachos Observatory on the Canary Island of La Palma at about 2200 m a.s.l. The telescope will receive a complete technological upgrade, including refurbished mirrors, a new drive system, and a new data acquisition system (as previously reported [17, 18, 19]) and will be equipped with a new camera, based entirely on G-APDs.

4.1. Mirrors

The existing glass mirrors of HEGRA CT3 will be exchanged for the mirrors originally built for an upgrade of HEGRA CT1 [20]. These mirrors are made entirely of aluminum, with an honeycomb inlay between the front and the back plates. They are of hexagonal shape, covering an area of 0.317 m^2 each. Being comprised of 30 of such mirrors, the total reflective surface of FACT amounts to 9.51 m^2. The over twelve years old mirrors have been re-machined by diamond-milling and subsequent coating with SiO_2. The distribution of the focal lengths is depicted in Fig. 1. It shows a very small spread of 8 mm around the mean focal length of 4.890 m.

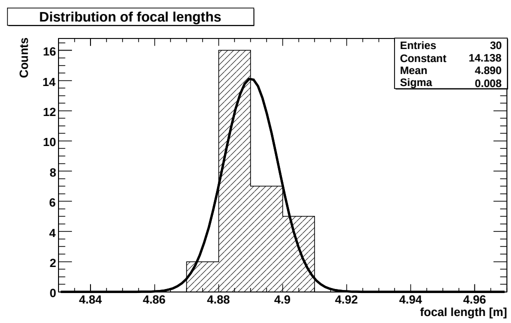

Figure 1: Distribution of the focal lengths of the FACT mirrors.

The spectral reflectivity of the mirrors is influenced by the coating thickness and thus by the homogeneity of the coating. The specular reflectivity of all mirrors was

measured to be constant within 4 % over the surface of every single mirror. The mean measured spectral reflectivity of all mirrors is shown in Fig. 2.

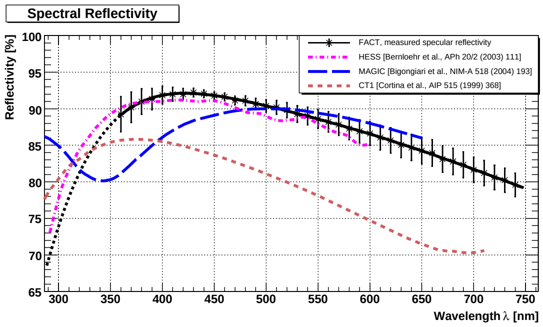

Figure 2: Mean measured reflectivity of the mirror facets for FACT. The standard deviations are given as error bars. The former reflectivity of the used mirrors (CT1) [20], as well as those for H.E.S.S. [21] and MAGIC [22] mirrors are given for comparison. The shape of the individual curves for CT1, MAGIC, and FACT is determined by the thickness of the SiO_2 coating via thin layer interference.

4.2. Drive System

The telescope drive will essentially be a down-scaled version of the drive system implemented in the MAGIC telescopes [23]. It is based on a programmable logic controller, accessible via Ethernet. New gear trains, fitting the new motors to the existing telescope system have been designed and all drive components are ready for installation.

4.3. Camera

The FACT camera will consist of 1440 G-APDs of the same type as already successfully operated in the test camera. Each G-APD will represent a pixel and will be equipped with a light guide and connected to a read-out channel. To account for the non-linear dependence of the gain of the G-APDs on their temperature, a feedback system for readjusting the bias voltage, based on an external temperature-stabilized LED pulser has been developed and extensively tested [24]. Taking into account the isotropic angular acceptance of the used G-APDs [7], a new design for non-imaging light concentrators made of UV transparent plexiglass has been made [25]. These light concentrators have a parabolic shape, guiding the incident light with total reflections from a hexagonal entrance to a square exit window matching the sensitive area of the G-APDs. This scheme allows one to arrange the pixels in a hexagonal pattern, thus matching the requirements of a minimal angular dependence of light collection used for advanced analysis methods developed for Cherenkov astronomy, as e.g. introduced in [26]. In contrast to a

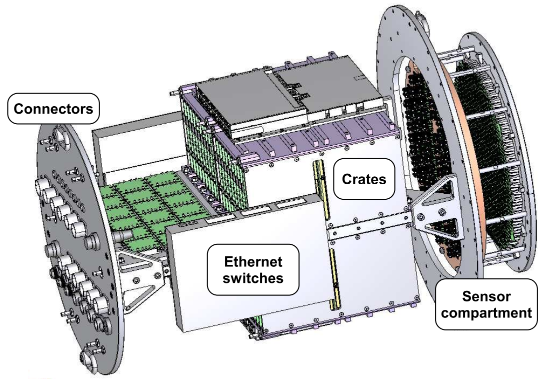

Figure 3: Conceptual drawing of the FACT camera. The length is 81.2 cm, the diameter amounts to 53.2 cm.

simple majority coincidence in the 36-pixel test camera, the trigger signal for FACT will be generated by a signal over threshold logic for every analog sum of 9 adjacent pixels, arranged in non-overlapping patches. The data acquisition (DAQ) system will be based on the DRS4 [27], which is an improved successor of the DRS2, used in the test camera. This allows for higher sampling rates (up to 5 GSamples/s) and a significantly reduced dead-time. The trigger logic and the DAQ are housed in water cooled crates, located directly behind the sensor plane inside the camera (Fig. 3). The data transfer down from the telescope will be handled via optical link Ethernet connections.

4.4. Software

During the design phase of the software special care was taken to comply with many standards already used by software for the MAGIC telescopes. The fully functional analysis software package MARS [28, 29] is at hand and can be used with only a few changes for the analysis of FACT data. For the Monte Carlo simulations, CORSIKA [30] air-shower simulations and the recently developed detector simulation subroutines in MARS CheObs [31] will be used. First simulations based on this software show very promising results [32].

5. Outlook

The construction of the camera as well as the assembly of the new telescope components will be carried out during this winter, so that commissioning will start in early 2011. A successful test of the novel G-APD camera will be a first step to consider the new photosensors for the next generation of IACTs, including CTA. FACT itself might be the first telescope to be

included in a world-wide network of Cherenkov telescopes [33, 34] for monitoring bright blazars in the northern hemisphere [35].

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